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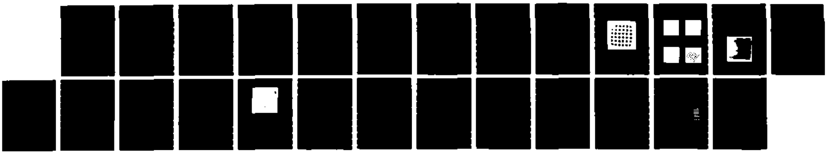

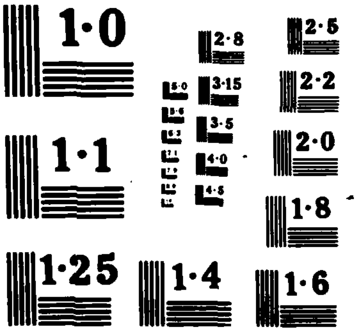

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A COHERENT FUSED SILICA FIBEROPTIC ARRAY

Galileo Electro-Optics Corporation
Galileo Park
Sturbridge, MA 01518

July 1986

US ARMY BALLISTIC RESEARCH LABORATORY
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Imagescopes greater than 10 meters in length are desirable for application in sighting and fire-control problems. However, conventional glasses do not transmit sufficient light for use in lengths greater than four or five meters. Fused silica optical fiber with a sufficiently low attenuation coefficient for transmitting over great lengths is available. The present work was undertaken to demonstrate the feasibility of fabricating a large format coherent fiber bundle from fused silica. Phase I of this project successfully demonstrated

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20. ABSTRACT (Continued)

the ability to make a 60-micron, 6 x 6 element multifiber, the basic building block of the coherent array. The goal of Phase II, the subject of the present report, was to fabricate a coherent, fused silica fiber array measuring one meter long with a resolution of 50 linepairs/mm.

This report describes the successful fabrication of the imagescope and documents the resolution (>50 linepairs/mm), the transmission (>40%), and the numerical aperture (.26 @ 1050 nm to .29 @ 400 nm). The feasibility of fabricating fused silica coherent bundles is demonstrated, and the steps required to make an 11 meter long imagescope are identified.

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I. BACKGROUND

Coherent fiber-optics offer great potential for application to sighting systems. However, optical fibers currently made from mixed silicate glasses exhibit attenuation coefficients as high as 2000 dB/km or more and are subject to optical blemishes arising from imperfections in the glass--particularly at the core/clad interface. Such high attenuation practically limits coherent fiber bundles to lengths of about three or four meters. This situation restricts the application of various electro-optical imaging techniques to sighting and fire-control problems.

Fused silica offers great material improvement over conventional silicate glasses. After twenty years of development for the communications industry, optical fibers made from fused silica are available with attenuation coefficients as low as 1.0 dB/km. In addition, Chemical Vapor Deposition (CVD) process used to manufacture preforms for such fiber results in near perfect, blemish free material because CVD processes are largely immune from the limitations of conventional silicate melting technology. Although communications quality fiber is not needed for the present application, there exist intermediate quality fused silica materials which exhibit attenuation coefficients between 10 and 100 dB/km. Made with CVD technology similar to that used to make communications fiber, such material provides an ideal opportunity for facilitating the application of state-of-the-art imaging technology to sighting and fire-control problems.

Galileo has developed technology for making coherent fiber bundles from conventional silicate glasses. Cane made of 1-5 mm diameter glass rods with an appropriate optical cladding is laid up into a square array and drawn into a square multifiber. The square shape of the multifiber permits it to be laid into a coherent bundle in which space is filled. This same technology can, in principle, be applied to fused silica. The key to developing fused silica coherent bundles is developing the ability to draw square multifiber from fused silica.

The present program is a two-phase effort to develop coherent imaging bundles from fused silica. The goal of Phase I was to develop and characterize a 60-micron, 6 x 6 square multifiber array from fused silica. The goal of Phase II, the subject of the present report, is to fabricate a one meter long, 3 x 4 mm coherent fiberoptic array from fused silica and to demonstrate a resolution of at least 50 linepairs/mm.

In Phase I, the ability to draw a square, 6 x 6 array of 60-micron fused silica multifiber was successfully demonstrated.[1] The mechanics of the draw were shown to be a straightforward extension of the technology previously developed at Galileo for mixed silicate glasses. Further, some of the preform requirements for both mechanical and optical performance of the multifiber were identified. The present report describes the successful fabrication and characterization of a one meter long, 4 x 4 mm coherent fiberoptic array.

II. IMAGESCOPE MANUFACTURE

The drawing of multifiber consists of three steps, drawing cane, laying the cane into an array, and drawing the array into multifiber. The cane is drawn from the preform down to a diameter of 1.5 mm in one meter lengths. The

cane is sorted and assembled in a 6 x 6 element square array. The individual cane elements fuse together in the hot zone of the furnace during the draw to form a solid square fiber. The resulting 60 micron multifiber has 36, eight micron optical cores held together in a matrix of low index cladding material. The secret to drawing good quality square multifiber is to find a combination of draw speed and temperature which permits consolidation of the individual elements without distortion.

To assemble an imagescope, the fiber is laid on a traversing drum and hand packed so that each multifiber is in intimate contact with its neighbors. Epoxy is brushed onto the multifibers to hold them together. The epoxy is partially cured and the ribbons of multifiber are removed from the drum. A number of ribbons are assembled vertically and pressed to form a solid block of completely cured epoxy holding the multifiber ribbons firmly together. The epoxied multifiber block is precisely cut to yield a coherent assembly of optical elements.

III. FUSED SILICA MULTIFIBER

Fused silica fiber is drawn in the same manner as conventional glass fiber. A preform is fed vertically into the top of a tube furnace and heated to a temperature within the working range of the glass. The fiber is drawn from the bottom of the furnace and spooled on a drum. The size of the fiber is controlled by the ratio of the feed speed to the draw speed. The primary difference between drawing fused silica and conventional glasses is the high temperature (~2000°C) required for fused silica.

A. Equipment

A high temperature draw tower located in a Class 100 Clean Room was used for the present work.

The high temperature furnace is equipped with an yttria-stabilized zirconia muffle tube coupled to a radio frequency generated field. Temperatures of 1400 to 2300°C are controlled by a three mode controller using an IR temperature sensing head focused on the stabilized zirconia tube. The preform or array is fed into the furnace by an electrically driven screw assembly. The fiber is pulled from the preform by pinch wheels and spooled onto drums. Fiber size is controlled by the ratio of feed speed to draw speed at constant drawing temperature.

B. Preforms

Preforms suitable for making fused silica optical fiber are currently made in a variety of ways. A relatively high index core with a lower index cladding is required. This configuration is achieved in practice by one of two methods. In the first, the high index core is made from Ge or P-doped fused silica, and the low index cladding is made from pure fused silica. In the second, the high index core is made from pure fused silica while the cladding is made from B- or F-doped fused silica. (Boron and fluorine are the only two dopants which will lower the refractive index of fused silica.)

In Phase I of this program, preforms made by Heraeus Amersil (SS-1.4) were used to demonstrate a square multifiber. This preform had a pure fused

silica core, an F-doped fused silica optical cladding, and an outer buffer layer of pure fused silica. The preform was successfully drawn into a 60-micron, 6 x 6 multifiber array. However, the outer fused silica buffer layer consolidated in the interstices and formed an extraneous waveguide in the fiber structure, resulting in crosstalk or leakage of light between the individual fiber elements. The effect is shown in Figure 1.

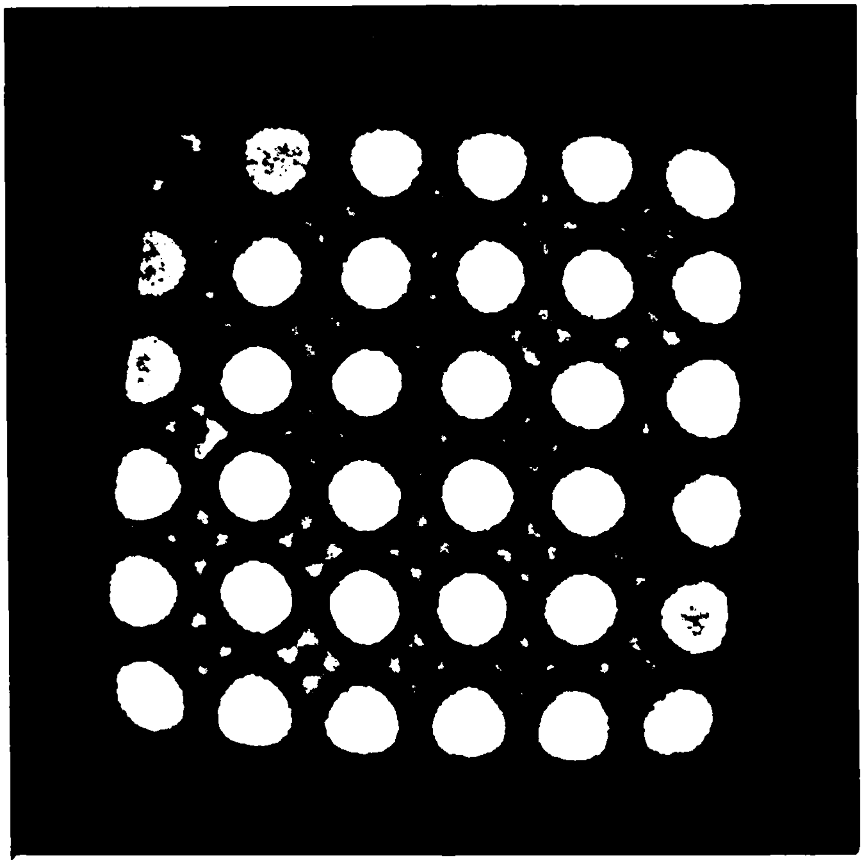
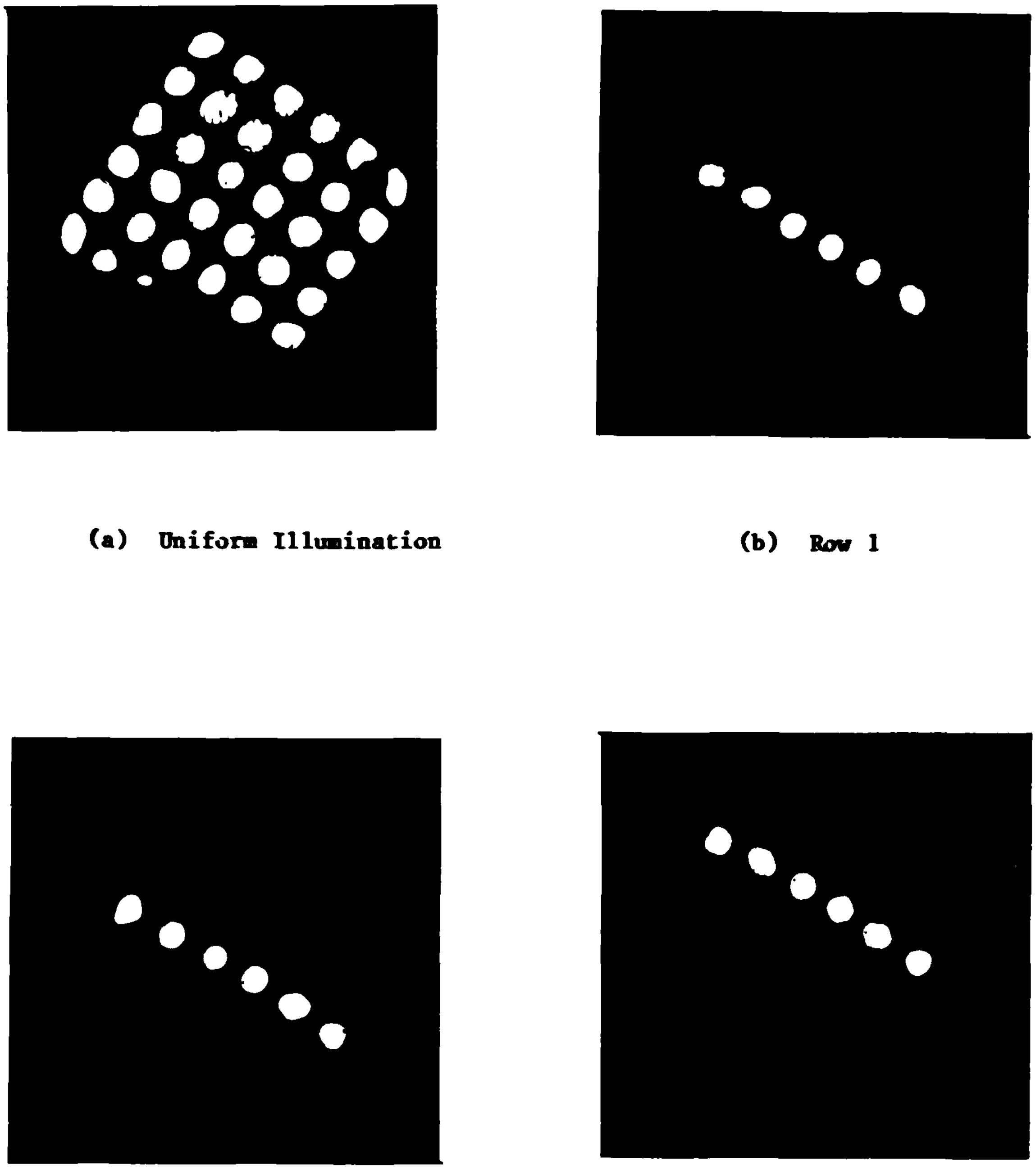


Figure 1. Effect of Extraneous Waveguide in Multifiber Made from Heraeus Amersil's SS-1.4 Preform

In Phase II, preforms with Ge-doped fused silica cores and pure fused claddings were used. This eliminated the extraneous waveguide effect and resulted in an array of optically independent conducting elements. The independence of the elements is demonstrated in Figure 2. Figures 2a through 2d are photomicrographs of the output end of a multifiber array under different illumination conditions. In Figure 2a the end was uniformly illuminated. Note that the individual cores are all illuminated, and no light is seen emanating from the continuous cladding area.



(a) Uniform Illumination

(b) Row 1

(c) Row 3

(d) Row 5

Figure 2. Demonstration of Element Independence in Multifiber Made from Preforms with Germania-Doped Silica Cores

In the subsequent pictures (Figures 2b-2d), the input was illuminated through a 10-micron rectangular mask which was indexed across the face of the array to illuminate one row of elements at a time. At the output, only the illuminated row of fibers is seen, showing the absence of crosstalk in the array.

IV. IMAGESCOPE

A. Fabrication

A prototype one meter long, 3 x 4 mm format imagescope was made using the process described in Section II. Step index preforms with Ge doped silica cores and pure silica claddings were drawn into 1.5 mm diameter lengths of cane; the pieces of cane were assembled into a 6 x 6 square array and drawn into multifiber. The multifiber was spooled onto a one meter circumference drum, handpacked and epoxied to form ribbons. The ribbons were assembled, pressed, and sliced in the epoxied region to form the coherent bundle which was then mounted into the hardware and polished.

A transmitted light photomicrograph of one end of the imagescope is shown in Figure 3. This clearly demonstrates the applicability of the existing technology to the manufacture of large format fused silica coherent arrays.

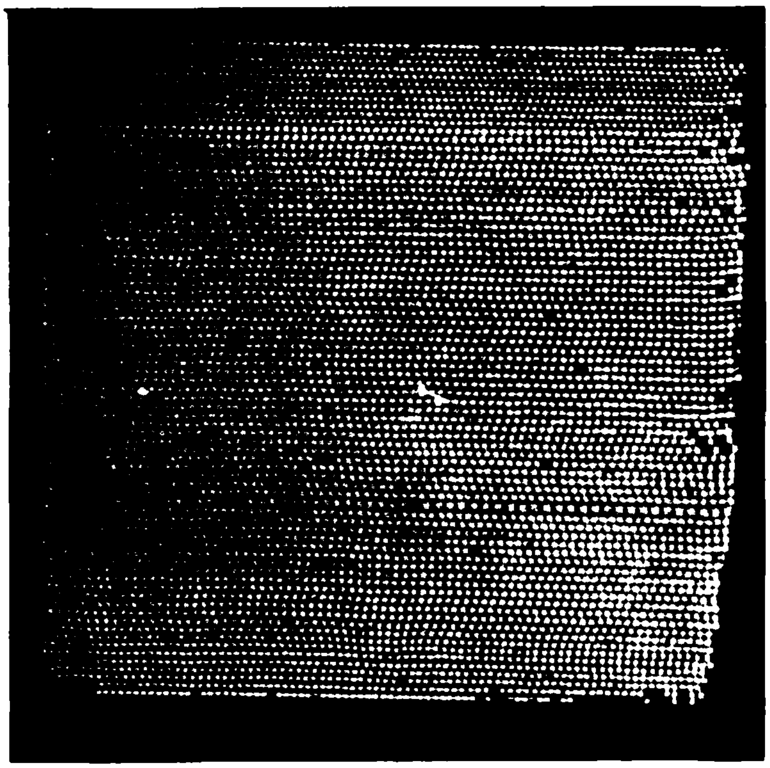


Figure 3. Photograph of 4 x 5 mm (3 x 4 mm Active Area), One Meter Long Imagescope

The few defects which are visible, broken fibers and irregular size and spacing of some fibers, are readily corrected.

The broken fibers result from the use of uncoated fiber for this project. The strength of fused silica fiber is known to be degraded rapidly through abrasion and atmospheric attack. The adoption of organic coatings has solved this problem in the communications fiber industry and is expected to do the same here.

Irregularly sized fibers are due to inadequate fiber size measurement equipment in the closed loop control system on the draw tower. The present system, designed for drawing round fiber, makes measurements on only one axis, and therefore it cannot differentiate between twist or size variation of a noncylindrical fiber. Addition of a two-axis measurement system to the tower will permit effective use of the closed loop size control system. Such a system is expected to limit fiber size variations to about 1%.

Irregular spacing of fibers is caused by the size variations mentioned above, as well as the need to handpack the fiber on the drum. An automatic spooling system with appropriate tension and indexing controls is required to eliminate handpacking and control fiber spacing.

B. Optical Characterization

The attenuation coefficients of separately fabricated 6 x 6 multifibers made from graded-index and step-index material were measured as a function of wavelength and the results plotted in Figure 4, along with those for a 100-micron monofiber of graded-index material. The attenuation in the multifiber arrays ranged from a low of about .26 dB/m in the step-index material to a high of about .55 dB/m in the graded-index material. The losses in the monofiber were significantly less than those in the multifiber arrays (about .002 dB/m at 850 nm). The differences are believed due to less than optimal core/clad ratios for multifiber fabrication and to the relative difficulty in controlling fiber geometry in the drawing of multifiber compared to monofiber. In the future, adoption of a system designed to measure the size of square fibers will permit use of the same closed loop control system to control multifiber size during the draw as is now used for monofiber.

Transmission for the imagescope was determined by measuring the detector response at each wavelength for a given aperture mask placed in front of the imagescope. Collimated light was then launched into the input end of the imagescope through the aperture mask and the output light level was measured with the detector butted against the output end of the imagescope. A reference level was determined by placing the detector behind the mask and measuring the incident light level. Transmission was reported as the ratio of the light output level to the reference level and therefore included all of the following effects: reflection, attenuation, packing fraction, core/clad ratio, and dead fibers. The transmission was approximately 40% across the visible and near IR; a plot of transmission vs. wavelength is shown in Figure 5.

The numerical aperture (NA) of the imagescope was measured by rotating the input end face (centered on the axis of rotation) within a wide, collimated beam of light, while recording the light transmission at the

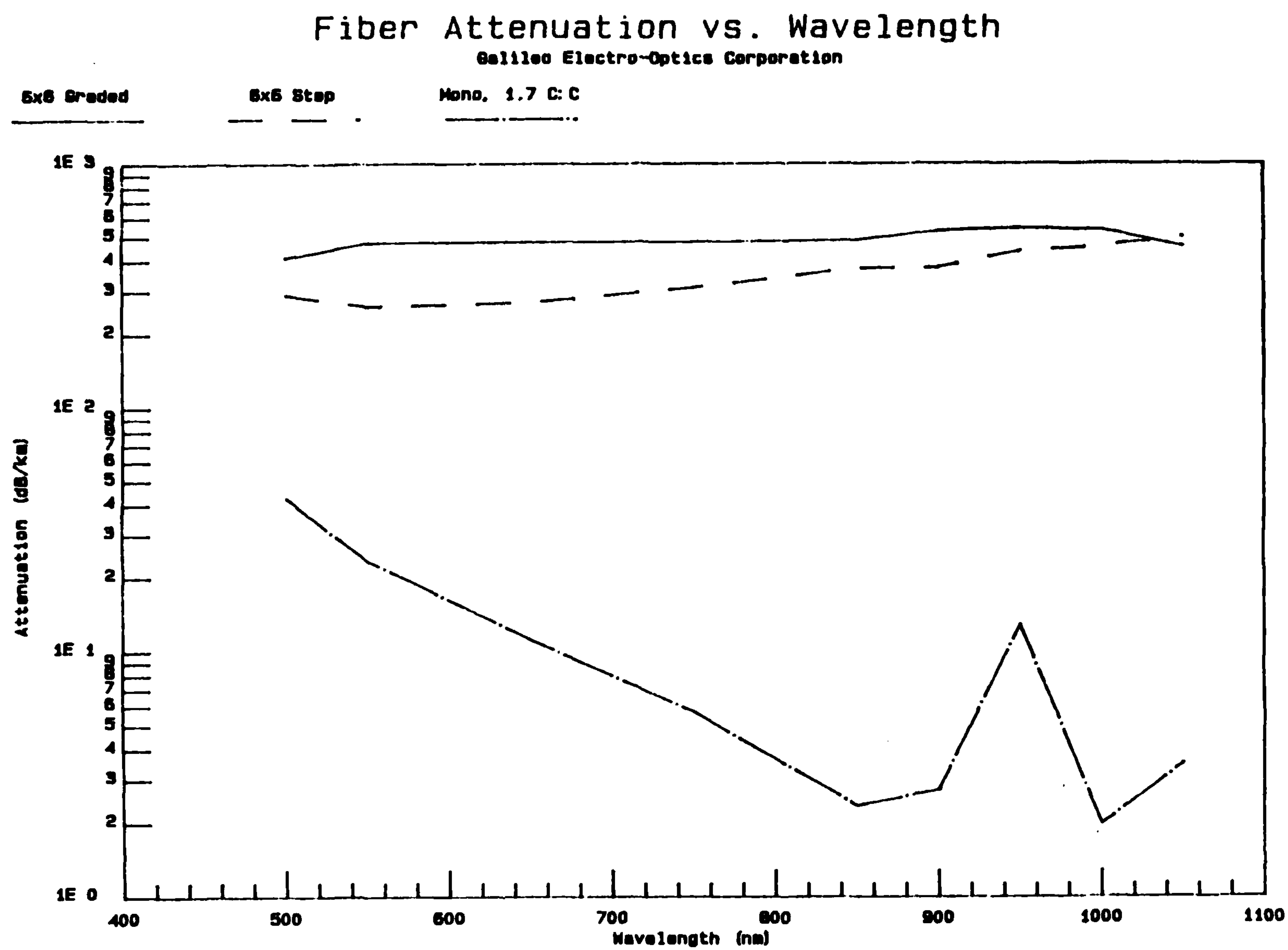


Figure 4. Fiber Attenuation vs. Wavelength

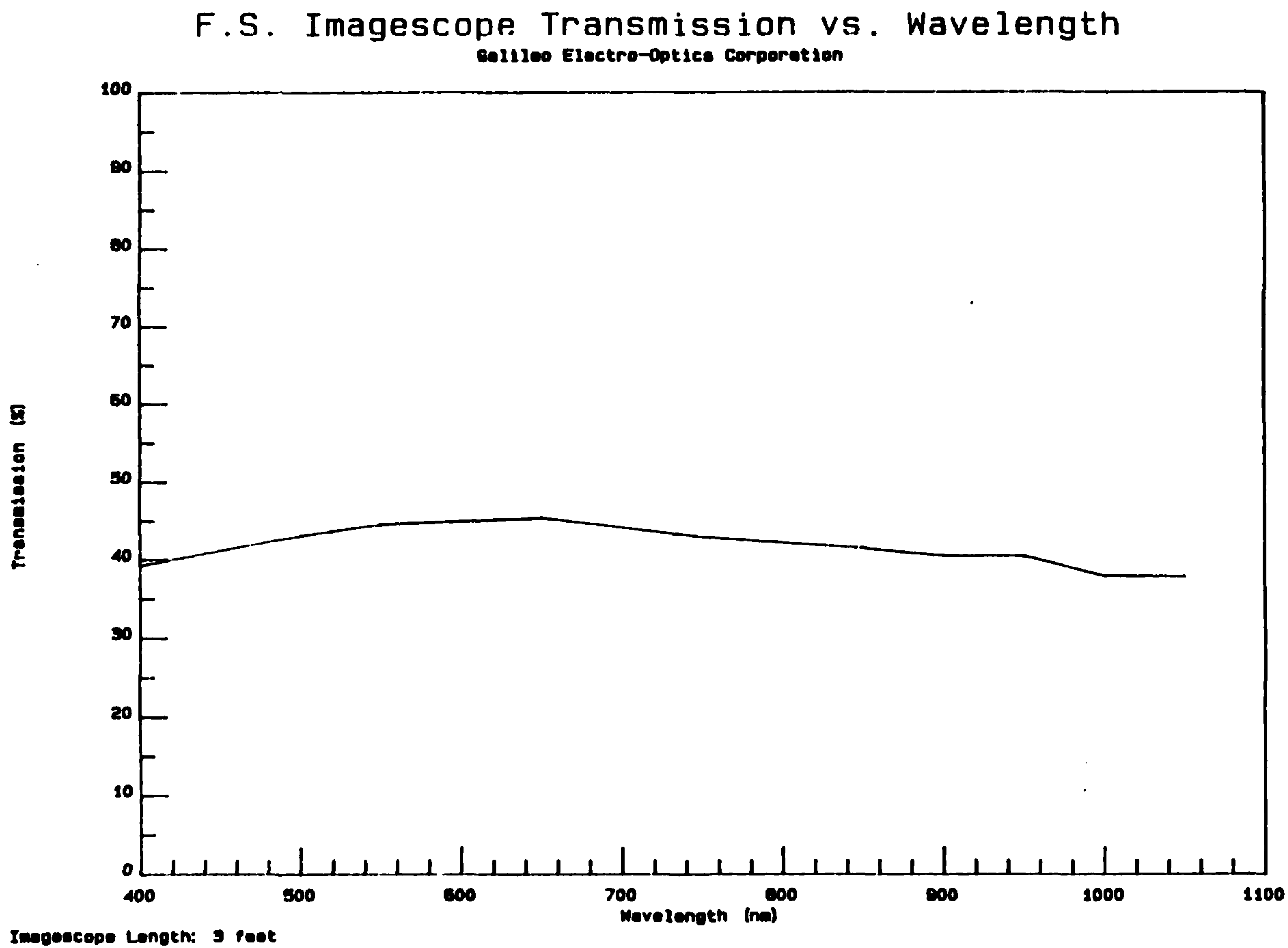


Figure 5. Imagescope Transmission vs. Wavelength

opposite end. A variation of light intensity vs. angular position was approximately Gaussian. The NA is defined to be the sine of the half-angle at 5% of the maximum intensity and ranges from .29 at 400 nm to .26 at 1050 nm. A plot of NA versus wavelength is shown in Figure 6.

The resolving power of the imagescope was evaluated by photographing a standard Air Force Resolution Target through the imagescope. The resolving power is given by the smallest resolution element that can be distinguished in the target. A photomicrograph of a resolution target taken through the imagescope is shown in Figure 7. It clearly shows a resolution in excess of 50 linepairs/mm, the goal for this program.

V. CONCLUSIONS AND RECOMMENDATIONS

The present task was to fabricate and characterize a one meter long, 4 x 4 mm coherent bundle from fused silica. The desired resolution was 50 linepairs/mm. The object of this effort was to demonstrate the feasibility of making large format imagescopes in lengths suitable for application in sighting and fire-control applications. A one meter long, 4 x 4 mm format fused silica imagescope has been successfully fabricated utilizing the technology developed at Galileo Electro-Optics Corporation for making large format imagescopes from common silicate glasses. This is believed to be the first fused silica imagescope of it's kind in the world. The imagescope successfully demonstrated relative transmission in excess of 40% in the visible and near-infrared portions of the spectrum, a numerical aperture between .26 and .29 over the same spectral range and resolution in excess of the required 50 linepairs/mm. This step clearly shows the feasibility of developing large format imagescopes in lengths suitable for application in electro-optic sighting and fire control problems.

Extension of the present work to the fabrication of 11 meter imagescopes, a practical size for evaluation in its intended application, should be undertaken. Accomplishment of that task will require:

1. Development of a suitable protective coating for the square multifiber array;

2. Optimization of the preform to provide appropriate optical characteristics to interface with the system optics; and

3. Fabrication of a computer controlled spooler with automatic tension and indexing controls for laying up the long coherent bundle.

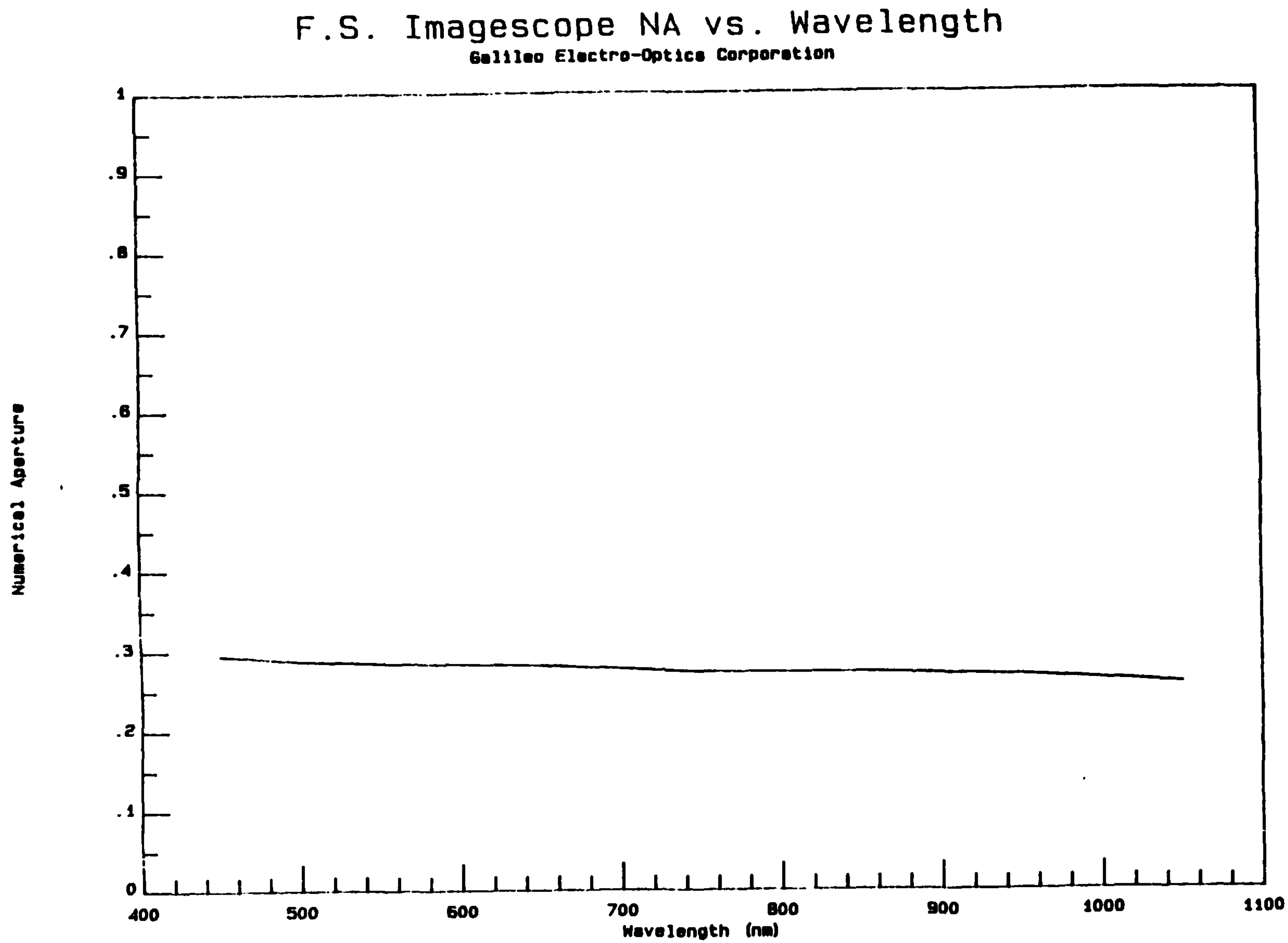


Figure 6. Imagescope NA vs. Wavelength

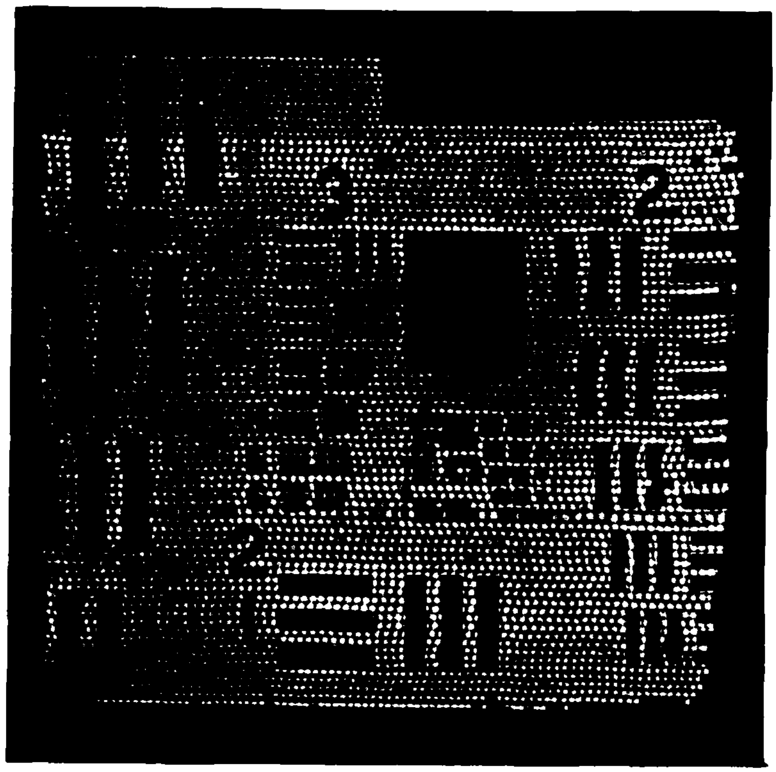


Figure 7. Imagescope Resolution

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